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INTEGRATED QUANTUM COLD POINT COOLERS

BACKGROUND OF THE INVENTION

1. Technical Field:

The present invention relates to devices for cooling
substances such as, for example, integrated circuit
chips, and more particularly, the present invention
relates to thermoelectric coolers.

2. Description of Related Art:

As the speed of computers continues to increase, the
amount of heat generated by the circuits within the
computers continues to increase. For many circuits and
applications, increased heat degrades the performance of
the computer. These circuits need to be cooled in order
to perform most efficiently. In many low end computers,
such as personal computers, the computer may be cooled
merely by using a fan and fins for convective cooling.
However, for larger computers, such as main frames, that
perform at faster speeds and generate much more heat,
these solutions are not viable.

Currently, many main-frames utilize vapor
compression coolers to cool the computer. These vapor
compression coolers perform essentially the same as the
central air conditioning units used in many homes.
However, vapor compression coolers are quite mechanically
complicated requiring insulation and hoses that must run
to various parts of the main frame in order to cool the
particular areas that are most susceptible to decreased
performance due to overheating.

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A much simpler and cheaper type of cooler are thermoelectric coolers. Thermoelectric coolers utilize a physical principle known as the Peltier Effect, by which DC current from a power source is applied across two

5 dissimilar materials causing heat to be absorbed at the junction of the two dissimilar materials. Thus, the heat is removed from a hot substance and may be transported to a heat sink to be dissipated, thereby cooling the hot substance. Thermoelectric coolers may be fabricated

10 within an integrated circuit chip and may cool specific hot spots directly without the need for complicated mechanical systems as is required by vapor compression coolers.

However, current thermoelectric coolers are not as

15 efficient as vapor compression coolers requiring more power to be expended to achieve the same amount of cooling. Furthermore, current thermoelectric coolers are not capable of cooling substances as greatly as vapor compression coolers. Therefore, a thermoelectric cooler

20 with improved efficiency and cooling capacity would be desirable so that complicated vapor compression coolers could be eliminated from small refrigeration applications, such as, for example, main frame computers, thermal management of hot chips, RF communication

25 circuits, magnetic read/write heads, optical and laser devices, and automobile refrigeration systems.

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SUMMARY OF THE INVENTION

The present invention provides a method for forming
a thermoelement for a thermoelectric cooler. In one
embodiment a first substrate having a plurality of

5   pointed tips separated by valleys wherein the substrate
is covered by a metallic layer, portions of the metallic
layer is covered by an insulator, and other portions of
the metallic layer are exposed is formed. The other
portions of the metallic layer that are exposed are

10   covered with a thermoelectric material overcoat. A
second substrate of thermoelectric material is then fused
to the pointed tip side of the first substrate by, for
example, heating the back of the first substrate to melt
the thermoelectric material overcoat or by passing

15   current through the pointed tips to induce Joule heating
and thereby melt the thermoelectric material overcoat.

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BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of

5 use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

Figure 1 depicts a high-level block diagram of a

10 Thermoelectric Cooling (TEC) device in accordance with the prior art;

Figure 2 depicts a cross sectional view of a thermoelectric cooler with enhanced structured interfaces in accordance with the present invention;

15 **Figure 3** depicts a planer view of thermoelectric cooler **200** in **Figure 2** in accordance with the present invention;

Figures 4A and **4B** depicts cross sectional views of tips that may be implemented as one of tips **250** in **Figure**

20 **2** in accordance with the present invention;

Figure 5 depicts a cross sectional view illustrating the temperature field of a tip near to a superlattice in accordance with the present invention;

Figure 6 depicts a cross sectional view of a

25 thermoelectric cooler with enhanced structured interfaces with all metal tips in accordance with the present invention;

Figure 7 depicts a cross-sectional view of a sacrificial silicon template for forming all metal tips

30 in accordance with the present invention;

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Figure 8 depicts a flowchart illustrating an exemplary method of producing all metal cones using a silicon sacrificial template in accordance with the present invention;

5   Figure 9 depicts a cross sectional view of all metal cones formed using patterned photoresist in accordance with the present invention;

Figure 10 depicts a flowchart illustrating an exemplary method of forming all metal cones using

10   photoresist in accordance with the present invention;

Figure 11 depicts a cross-sectional view of a thermoelectric cooler with enhanced structural interfaces in which the thermoelectric material rather than the metal conducting layer is formed into tips at the

15   interface in accordance with the present invention;

Figure 12 depicts a flowchart illustrating an exemplary method of fabricating a thermoelectric cooler in accordance with the present invention;

Figure 13 depicts a cross-sectional diagram

20   illustrating the positioning of photoresist necessary to produce tips in a thermoelectric material;

Figure 14 depicts a diagram showing a cold point tip above a surface for use in a thermoelectric cooler illustrating the positioning of the tip relative to the

25   surface in accordance with the present invention;

Figure 15 depicts a schematic diagram of a thermoelectric power generator; and

Figures 16A-16J depict cross sectional diagrams illustrating a process for fabricating thermoelements

30   with pointed tip interfaces in accordance with the present invention.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

     With reference now to the figures and, in particular, with reference to **Figure 1,** a high-level block diagram of a Thermoelectric Cooling (TEC) device is

5   depicted in accordance with the prior art. Thermoelectric cooling, a well known principle, is based on the Peltier Effect, by which DC current from power source **102** is applied across two dissimilar materials causing heat to be absorbed at the junction of the two

10   dissimilar materials. A typical thermoelectric cooling device utilizes p-type semiconductor **104** and n-type semiconductor **106** sandwiched between poor electrical conductors **108** that have good heat conducting properties. N-type semiconductor **106** has an excess of electrons,

15   while p-type semiconductor **104** has a deficit of electrons.

     As electrons move from electrical conductor **110** to n-type semiconductor **106,** the energy state of the electrons is raised due to heat energy absorbed from heat

20   source **112.** This process has the effect of transferring heat energy from heat source **112** via electron flow through n-type semiconductor **106** and electrical conductor **114** to heat sink **116.** The electrons drop to a lower energy state and release the heat energy in electrical

25   conductor **114.**

     The coefficient of performance, η, of a cooling refrigerator, such as thermoelectric cooler **100,** is the ratio of the cooling capacity of the refrigerator divided by the total power consumption of the refrigerator. Thus

30   the coefficient of performance is given by the equation:

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$$\eta = \frac{\alpha I T_c - \frac{1}{2} I^2 R - K \Delta T}{I^2 R + \alpha I \Delta T}$$

where the term $\alpha I T_c$ is due to the thermoelectric cooling, the term $\frac{1}{2} I^2 R$ is due to Joule heating backflow, the term $K \Delta T$ is due to thermal conduction, the term $I^2 R$ is due to

5   Joule loss, the term $\alpha I \Delta T$ is due to work done against the Peltier voltage, α is the Seebeck coefficient for the material, T_c is the temperature of the heat source, and ΔT is the difference in the temperature of the heat source from the temperature of the heat sink.

10   The maximum coefficient of performance is derived by optimizing the current, I, and is given by the following relation:

$$\eta_{max} = \left(\frac{T_c}{\Delta T} \right) \left[\frac{\gamma - T_h / T_c}{\gamma + 1} \right]$$

where

$$\gamma = \sqrt{1 + \frac{\alpha^2 \sigma}{\lambda} \left(\frac{T_h + T_c}{2} \right)}$$

15

and

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$$\varepsilon = \frac{\gamma - T_h / T_c}{\gamma + 1}$$

where ε is the efficiency factor of the refrigerator.
The figure of merit, ZT, is given by the equation:

$$ZT = \frac{\alpha^2 \sigma T}{\lambda}$$

5   where λ is composed of two components: λ_e, the component
due to electrons, and λ_L, the component due to the
lattice. Therefore, the maximum efficiency, ε, is
achieved as the figure of merit, ZT, approaches infinity.
The efficiency of vapor compressor refrigerators is
10   approximately 0.3. The efficiency of conventional
thermoelectric coolers, such as thermoelectric cooler **100**
in **Figure 1,** is typically less than 0.1. Therefore, to
increase the efficiency of thermoelectric coolers to such
a range as to compete with vapor compression
15   refrigerators, the figure of merit, ZT, must be increased
to greater than 2. If a value for the figure of merit,
ZT, of greater than 2 can be achieved, then the
thermoelectric coolers may be staged to achieve the same
efficiency and cooling capacity as vapor compression
20   refrigerators.

     With reference to **Figure 2,** a cross sectional view
of a thermoelectric cooler with enhanced structured
interfaces is depicted in accordance with the present

invention. Thermoelectric cooler **200** includes a heat
source **226** from which, with current **I** flowing as
indicated, heat is extracted and delivered to heat sink
202. Heat source **226** may be thermally coupled to a

5 substance that is desired to be cooled. Heat sink **202**
may be thermally coupled to devices such as, for example,
a heat pipe, fins, and/or a condensation unit to
dissipate the heat removed from heat source **226** and/or
further cool heat source **226**.

10   Heat source **226** is comprised of p- type doped
silicon. Heat source **226** is thermally coupled to n+ type
doped silicon regions **224** and **222** of tips **250**. N+ type
regions **224** and **222** are electrical conducting as well as
being good thermal conductors. Each of N+ type regions

15 **224** and **222** forms a reverse diode with heat source **226**
such that no current flows between heat source **226** and n+
regions **224** and **222**, thus providing the electrical
isolation of heat source **226** from electrical conductors
218 and **220**.

20   Heat sink **202** is comprised of p- type doped silicon.
Heat sink **202** is thermally coupled to n+ type doped
silicon region **204**. N+ type region **204** is electrically
conducting and is a good thermal conductor. N+ type
region **204** and heat sink **202** forms a reverse diode so

25 that no current flows between the N+ type region **204** and
heat sink **202**, thus providing the electrical isolation of
heat sink **202** from electrical conductor **208**. More
information about electrical isolation of thermoelectric
coolers may be found in commonly U.S. Patent No.

30 6,222,113, the contents of which are hereby incorporated
herein for all purposes.

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The need for forming reverse diodes with n+ and p-regions to electrically isolate conductor **208** from heat sink **202** and conductors **218** and **220** from heat source **226** is not needed if the heat sink **202** and heat source **226**

5　are constructed entirely from undoped non-electrically conducting silicon. However, it is very difficult to ensure that the silicon is entirely undoped. Therefore, the presence of the reverse diodes provided by the n+ and p- regions ensures that heat sink **202** and heat source **226**

10　are electrically isolated from conductors **208, 218,** and **220.** Also, it should be noted that the same electrical isolation using reverse diodes may be created other ways, for example, by using p+ type doped silicon and n- type doped silicon rather than the p- and n+ types depicted.

15　The terms n+ and p+, as used herein, refer to highly n doped and highly p doped semiconducting material respectively. The terms n- and p-, as used herein, mean lightly n doped and lightly p doped semiconducting material respectively.

20　Thermoelectric cooler **200** is similar in construction to thermoelectric cooler **100** in **Figure 1.** However, N-type **106** and P-type **104** semiconductor structural interfaces have been replaced with superlattice thermoelement structures **210** and **212** that are

25　electrically coupled by doped region **204** and electrical conductor **208.** Electrical conductor **208** may be formed from platinum (Pt) or, alternatively, from other conducting materials, such as, for example, tungsten (W), nickel (Ni), or titanium copper nickel (Ti/Cu/Ni) metal

30　films.

A superlattice is a structure consisting of alternating layers of two different semiconductor

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materials, each several nanometers thick. Thermoelement **210** is constructed from alternating layers of N-type semiconducting materials and the superlattice of thermoelement **212** is constructed from alternating layers

5   of P-type semiconducting materials. Each of the layers of alternating materials in each of thermoelements **210** and **212** is approximately 10 nanometers (nm) thick. A superlattice of two semiconducting materials has lower thermal conductivity, λ, and the same electrical

10   conductivity, σ, as an alloy comprising the same two semiconducting materials.

     In one embodiment, superlattice thermoelement **212** comprises alternating layers of p-type bismuth chalcogenide materials such as, for example, alternating

15   layers of Bi_2Te_3/Sb_2Te_3 with layers of $Bi_{0.5}Sb_{1.5}Te_3$, and the superlattice of thermoelement **210** comprises alternating layers of n-type bismuth chalcogenide materials, such as, for example, alternating layers of Bi_2Te_3 with layers of Bi_2Se_3. Other types of semiconducting materials may be

20   used for superlattices for thermoelements **210** and **212** as well. For example, rather than bismuth chalcogenide materials, the superlattices of thermoelements **210** and **212** may be constructed from cobalt antimony skutteridite materials.

25   Thermoelectric cooler **200** also includes tips **250** through which electrical current **I** passes into thermoelement **212** and then from thermoelement **210** into conductor **218**. Tips **250** includes n+ type semiconductor **222** and **224** formed into pointed conical structures with a

30   thin overcoat layer **218** and **220** of conducting material, such as, for example, platinum (Pt). Other conducting

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materials that may be used in place of platinum include, for example, tungsten (W), nickel (Ni), and titanium copper nickel (Ti/Cu/Ni) metal films. The areas between and around the tips **250** and thermoelectric materials **210**

5   and **212** should be evacuated or hermetically sealed with a gas such as, for example, dry nitrogen.

On the ends of tips **250** covering the conducting layers **218** and **220** is a thin layer of semiconducting material **214** and **216**. Layer **214** is formed from a P-type

10 material having the same Seebeck coefficient, α, as the nearest layer of the superlattice of thermoelement **212** to tips **250**. Layer **216** is formed from an N-type material having the same Seebeck coefficient, α, as the nearest layer of thermoelement **210** to tips **250**. The P-type

15 thermoelectric overcoat layer **214** is necessary for thermoelectric cooler **200** to function since cooling occurs in the region near the metal where the electrons and holes are generated. The n-type thermoelectric overcoat layer **216** is beneficial, because maximum cooling

20 occurs where the gradient (change) of the Seebeck coefficient is maximum. The thermoelectric overcoats **214** and **216** are preferably in the range of 2-5 nanometers thick based upon present investigation.

By making the electrical conductors, such as,

25 conductors **110** in **Figure 1**, into pointed tips **250** rather than a planar interface, an increase in cooling efficiency is achieved. Lattice thermal conductivity, λ, at the point of tips **250** is very small because of lattice mismatch. For example, the thermal conductivity, λ, of

30 bismuth chalcogenides is normally approximately 1 Watt/meter*Kelvin. However, in pointed tip structures,

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such as tips **250**, the thermal conductivity is reduced,
due to lattice mismatch at the point, to approximately
0.1 Watts/meter*Kelvin. However, the electrical
conductivity of the thermoelectric materials remains

5   relatively unchanged. Therefore, the figure of merit,
ZT, may increased to greater than 2.5 for this kind of
material. Another type of material that is possible for
the superlattices of thermoelements **210** and **212** is cobalt
antimony skutteridites. These type of materials

10   typically have a very high thermal conductivity, λ,
making them normally undesirable. However, by using the
pointed tips **250**, the thermal conductivity can be reduced
to a minimum and produce a figure of merit, *ZT*, for these
materials of greater than 4, thus making these materials

15   very attractive for use in thermoelements **210** and **212**.

Another advantage of the cold point structure is
that the electrons are confined to dimensions smaller
than the wavelength (corresponding to their kinetic
energy). This type of confinement increases the local

20   density of states available for transport and effectively
increases the Seebeck coefficient. Thus, by increasing α
and decreasing λ, the figure of merit ZT is increased.

Conventional thermoelectric coolers, such as
illustrated in **Figure 1**, are capable of producing a

25   cooling temperature differential, ΔT, between the heat
source and the heat sink of around 60 Kelvin. However,
thermoelectric cooler **200** is capable of producing a
temperature differential greater than 100 Kelvin. Thus,
with two thermoelectric coolers coupled to each other,

30   cooling to temperatures in the range of liquid Nitrogen
(less than 100 Kelvin) is possible. However, different

materials may need to be used for thermoelements **210** and **212**. For example, bismuth telluride has a very low α at low temperature (i.e. less than -100 degrees Celsius). However, bismuth antimony alloys perform well at low

5   temperature.

Those of ordinary skill in the art will appreciate that the construction of the thermoelectric cooler in **Figure 2** may vary depending on the implementation taking into account the desired cooling, heat transfer capacity,

10   current and voltage supplies. For example, more or fewer rows of tips **250** may be included than depicted in **Figure 1**. The depicted example is not meant to imply architectural limitations with respect to the present invention.

15   With reference now to **Figure 3,** a planer view of thermoelectric cooler **200** in **Figure 2** is depicted in accordance with the present invention. Thermoelectric cooler **300** includes an n-type thermoelectric material section **302** and a p-type thermoelectric material section

20   **304**. Both n-type section **302** and p-type section **304** include a thin layer of conductive material **306** that covers a silicon body.

Section **302** includes an array of conical tips **310** each covered with a thin layer of n-type material **308** of

25   the same type as the nearest layer of the superlattice for thermoelement **210**. Section **304** includes an array of conical tips **312** each covered with a thin layer of p-type material **314** of the same type as the nearest layer of the superlattice for thermoelement **212**.

30   With reference now to **Figures 4A** and **4B,** a cross sectional views of tips that may be implemented as one of

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tips **250** in **Figure 2** is depicted in accordance with the present invention. Tip **400** includes a silicon cone **402** that has been formed with a cone angle of approximately 35 degrees. A thin layer **404** of conducting material,
5   such as platinum (Pt), overcoats the silicon **402**. A thin layer of thermoelectric material **406** covers the very end of the tip **400**. The cone angle after all layers have been deposited is approximately 45 degrees. The effective point radius of tip **400** is approximately 50
10 nanometers.

Tip **408** is an alternative embodiment of a tip, such as one of tips **250**. Tip **408** includes a silicon cone **414** with a conductive layer **412** and thermoelectric material layer **410** over the point. However, tip **408** has a much
15 sharper cone angle than tip **400**. The effective point radius of tip **408** is approximately 10 nanometers. It is not known at this time whether a broader or narrower cone angle for the tip is preferable. In the present embodiment, conical angles of 45 degrees for the tip, as
20 depicted in **Figure 4A,** have been chosen, since such angle is in the middle of possible ranges of cone angle and because such formation is easily fabricated from silicon with a platinum overcoat. This is because a KOH etch along the <100> plane of silicon naturally forms a cone
25 angle of 54 degrees. Thus, after the conductive and thermoelectric overcoats have been added, the cone angle is approximately 45 degrees.

With reference now to **Figure 5,** a cross sectional view illustrating the temperature field of a tip near to
30 a superlattice is depicted in accordance with the present invention. Tip **504** may be implemented as one of tips **250**

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in **Figure 2**. Tip **504** has a effective tip radius at its
sharpest point, *a*, of 10-50 nanometers. Thus, the
temperature field is localized to a very small distance,
r, approximately equal to 2a or around 20-100 nanometers.

5   Superlattice **502** need to be only a few layers thick to
limit heat flow. Therefore, using pointed tips, a
thermoelectric cooler with only 5-10 layers for the
superlattice is sufficient.

   Thus, fabricating a thermoelectric cooler, such as,

10   for example, thermoelectric cooler **200**, is simplified,
since only a few layers of the superlattice must be
formed. Also, thermoelectric cooler **200** can be
fabricated very thin (on the order of 100 nanometers
thick) as contrasted to conventional thermoelectric

15   coolers which are on the order of 3 millimeters or
greater in thickness.

   Other advantages of a thermoelectric cooler with
pointed tip interfaces in accordance with the present
invention include minimization of the thermal

20   conductivity through the thermoelements, such as
thermoelements **210** and **212** in **Figure 2**, because of the
tip interfaces. Also, the temperature/potential drops
are localized to an area near the tips, effectively
allowing scaling to sub-100-nanometer lengths.

25   Furthermore, using pointed tips minimizes the number
layers needed for superlattice thermoelements **210** and
212. The present invention also permits
electrodeposition of thin film structures. The smaller
dimensions also allow for monolithic integration of

30   n-type and p-type thermoelements.

   The thermoelectric cooler of the present invention
may be utilized to cool items, such as, for example,

specific spots within a main frame computer, lasers, optic electronics, photodetectors, and PCR in genetics.

With reference now to **Figure 6,** a cross sectional view of a thermoelectric cooler with enhanced structured interfaces with all metal tips is depicted in accordance with the present invention. Although the present invention has been described above as having tips **250** constructed from silicon cones constructed from the n+ semiconducting regions **224** and **222**, tips **250** in **Figure 2** may be replaced by tips **650** as depicted in **Figure 6.** Tips **650** have all metal cones **618** and **620**. In the depicted embodiment, cones **618** and **620** are constructed from copper and have a nickel overcoat layer **660** and **662.** Thermoelectric cooler **600** is identical to thermoelectric cooler **200** in all other respects, including having a thermoelectric overcoat **216** and **214** over the tips **650.** Thermoelectric cooler **600** also provides the same benefits as thermoelectric cooler **200.** However, by using all metal cones rather than silicon cones covered with conducting material, the parasitic resistances within the cones become very low, thus further increasing the efficiency of thermoelectric cooler **600** over the already increased efficiency of thermoelectric cooler **200.** The areas surrounding the contact areas of tips **650** to thermoelectric materials **210** and **212** should be vacuum or hermetically sealed with a low-thermal conductivity gas, such as, for example, argon.

Also, as in **Figure 2,** heat source **226** is comprised of p- type doped silicon. In contrast to **Figure 2,** however, silicon heat source **226** is thermally coupled to n+ type doped silicon regions **624** and **622** but does not

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form part of the tipped structure **650** as did silicon regions **224** and **222** do in **Figure 2**. N+ type doped silicon regions **624** and **622** do still perform the electrical isolation function performed by regions **224**

5   and **222** in **Figure 2**.

Several methods may be utilized to form the all metal cones as depicted in **Figure 6**. For example, with reference now to **Figure 7**, a cross-sectional view of a sacrificial silicon template that may be used for forming

10   all metal tips is depicted in accordance with the present invention. After the sacrificial silicon template **702** has been constructed having conical pits, a layer of metal may be deposited over the template **702** to produce all metal cones **704**. All metal cones **704** may then be

15   used in thermoelectric cooler **600**.

With reference now to **Figure 8**, a flowchart illustrating an exemplary method of producing all metal cones using a silicon sacrificial template is depicted in accordance with the present invention. To begin, conical

20   pits are fabricated by anisotropic etching of silicon to create a mold (step **802**). This may be done by a combination of KOH etching, oxidation, and/or focused ion-beam etching. Such techniques of fabricating silicon pits are well known in the art.

25   The silicon sacrificial template is then coated with a thin sputtered layer of seed metal, such as, for example, titanium (step **804**). Next, copper is electrochemically deposited to fill the valleys (conical pits) in the sacrificial silicon template. (step **806**).

30   The top surface of the copper is then planarized (step **808**). Methods of planarizing a layer of metal are well

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known in the art. The silicon substrate is then removed
by selective etching methods well known in the art (step
810). The all metal cones produced in this manner may
then be covered with a coat of another metal, such as,
5   for example, nickel, and then with an ultra-thin layer of
thermoelectric material. The nickel overcoat aids in
electrodeposition of the thermoelectric material
overcoat.

One advantage to this method of producing all metal
10   cones is that the silicon substrate mold is reusable if
the copper is peeled from the silicon substrate as the
separation process. The silicon substrate mold may be
reused up to around 10 times before the mold degrades and
becomes unusable.

15   Forming a template in this manner is very well
controlled and produces very uniform all metal conical
tips since silicon etching is very predictable and can
calculate slopes of the pits and sharpness of the cones
produced to a very few nanometers.

20   Other methods of forming all metal cones may be used
as well. For example, with reference now to **Figure 9,** a
cross sectional view of all metal cones **902** formed using
patterned photoresist is depicted in accordance with the
present invention. In this method, a layer of metal is
25   formed over the bottom portions of a partially fabricated
thermoelectric cooler. A patterned photoresist **904-908** is
then used to fashion all metal cones **902** with a direct
electrochemical etching method. Often the tips are
further sharpened by focused ion beam milling.

30   With reference now to **Figure 10,** a flowchart
illustrating an exemplary method of forming all metal
cones using photoresist is depicted in accordance with the

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present invention. To begin, small sections of
photoresist are patterned over a metal layer, such as
copper, of a partially fabricated thermoelectric cooler
(step **1002**). The photoresist may be patterned in an array

5   of sections having photoresist wherein each area of
photoresist within the array corresponds to areas in which
tips to the all metal cones are desired to be formed. The
metal is then directly etched electrochemically (step
1004) to produce cones **902** as depicted in **Figure 9**. The

10   photoresist is then removed and the tips of the all metal
cones may then be coated with another metal, such as, for
example, nickel (step **1006**). The second metal coating
over the all metal cones may then be coated with an
ultra-thin layer of thermoelectric material (step **1008**).

15   Thus, all metal cones with a thermoelectric layer on the
tips may be formed which may used in a thermoelectric
device, such as, for example, thermoelectric cooler **600**.
The all metal conical points produced in this manner are
not as uniform as those produced using the method

20   illustrated in **Figure 8**. However, this method currently
is cheaper and therefore, if cost is an important factor,
may be a more desirable method.

The depicted methods of fabricating all metal cones
are merely examples. Other methods may be used as well

25   to fabricate all metal cones for use with thermoelectric
coolers. Furthermore, other types of metals may be used
for the all metal cone other than copper.

With reference now to **Figure 11**, a cross-sectional
view of a thermoelectric cooler with enhanced structural

30   interfaces in which the thermoelectric material rather
than the metal conducting layer is formed into tips at
the interface is depicted in accordance with the present

invention. Thermoelectric cooler **1100** includes a cold
plate **1116** and a hot plate **1102,** wherein the cold plate
1116 is in thermal contact with the substance that is to
be cooled. Thermal conductors **1114** and **1118** provide a

5   thermal couple between electrical conducting plates **1112**
and **1120** respectively. Thermal conductors **1114** and **1118**
are constructed of heavily n doped (n+) semiconducting
material that provides electrical isolation between cold
plate **1116** and conductors **1112** and **1120** by forming

10 reverse biased diodes with the p- material of the cold
plate **1116**. Thus, heat is transferred from the cold
plate **1116** through conductors **1112** and **1120** and
eventually to hot plate **1102** from which it can be
dissipated without allowing an electrical coupling

15 between the thermoelectric cooler **1100** and the substance
that is to be cooled. Similarly, thermal conductor **1104**
provides a thermal connection between electrical
conducting plate **1108** and hot plate **1102,** while
maintaining electrical isolation between the hot plate

20 and electrical conducting plate **1108** by forming a reverse
biased diode with the hot plate **1102** p- doped
semiconducting material as discussed above. Thermal
conductor **1104** is also an n+ type doped semiconducting
material. Electrical conducting plates **1108, 1112,** and

25 **1120** are constructed from platinum (Pt) in this
embodiment. However, other materials that are both
electrically conducting and thermally conducting may be
utilized as well. Also, it should be mentioned that the
areas surrounding tips **1130-1140** proximate thermoelectric

30 materials **1122** and **1110** should be evacuated to produce a
vacuum or should be hermetically sealed with a low

thermal conductivity gas, such as argon.

In this embodiment, rather than providing contact between the thermoelements and the heat source (cold end) metal electrode (conductor) through an array of points having metal in the point electrodes as in **Figures 2** and **6**, the array of points of contact between the thermoelement and the metal electrode is provided by an array of points **1130-1140** composed of thermoelements **1124** and **1126**. The tips **1130-1140** of the present embodiment may be formed from single crystal or polycrystal thermoelectric materials by electrochemical etching.

In one embodiment, thermoelement **1124** is comprised of a super lattice of single crystalline Bi_2Te_3/Sb_2Te_3 and $Bi_{0.5}Sb_{1.5}Te_3$ and thermoelement **1126** is formed of a super lattice of single crystalline Bi_2Te_3/Bi_2Se_3 and $Bi_2Te_{2.0}Se_{0.1}$. Electrically conducting plate **1120** is coated with a thin layer **1122** of the same thermoelectric material as is the material of the tips **1130-1134** that are nearest thin layer **1120**. Electrically conducting plate **1112** is coated with a thin layer **1110** of the same thermoelectric material as is the material of the tips **1136-1140** that are nearest thin layer **1112**.

With reference now to **Figure 12**, a flowchart illustrating an exemplary method of fabricating a thermoelectric cooler, such as, for example, thermoelectric cooler **1100** in **Figure 11**, is depicted in accordance with the present invention. Optimized single crystal material is first bonded to a metal electrode **1301** by conventional means or the metal electrode is deposited onto the single crystal material to form the electrode connection pattern (step **1202**) as depicted in

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Figure 13. The other side of the thermoelectric material **1314** is then patterned (step **1204**) by using photoresist **1302-1306** as a mask and the metal electrode as an anode in an electrochemical bath to etch the surface (step

5   **1206**). The tips **1308-1312** as depicted in **Figure 13** are formed by controlling and stopping the etching process at appropriate times.

A second single crystal substrate is thinned by chemical-mechanical polishing and then electrochemically

10 etching the entire substrate to nanometer films (step **1210**). The second ultra-thin substrate forms the cold end. The two substrates (the one with the ultra-thin thermoelectric material and the other with the thermoelectric tips) are then clamped together with light

15 pressure (step **1212**). This structure retains high crystallinity in all regions other than the interface at the tips. Also, similar methods can be used to fabricate polycrystalline structures rather than single crystalline structures.

20 With reference now to **Figure 14**, a diagram showing a cold point tip above a surface for use in a thermoelectric cooler illustrating the positioning of the tip relative to the surface is depicted in accordance with the present invention. Although the tips, whether

25 created in as all-metal or metal coated tips or as thermoelectric tips have been described thus far as being in contact with the surface opposite the tips. However, although the tips may be in contact with the opposing surface, it is preferable that the tips be very near the

30 opposing surface without fully touching the surface as depicted in **Figure 14**. The tip **1402** in **Figure 14** is situated near the opposing surface **1404** but is not in

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physical contact with the opposing surface. Preferably, the tip **1402** should be a distance **d** on the order of 1 nanometer or less from the opposing surface **1404**. In practice, with a thermoelectric cooler containing

5   thousands of tips, some of the tips may be in contact with the opposing surface while others are not in contact due to the deviations from a perfect plane of the opposing surface.

By removing the tips from contact with the opposing

10   surface, the thermal conductivity between the cold plate and the hot plate of a thermoelectric cooler may be reduced. Electrical conductivity is maintained, however, due to tunneling of electrons between the tips and the opposing surface.

15   The tips of the present invention have also been described and depicted primarily as perfectly pointed tips. However, as illustrated in **Figure 14,** the tips in practice will typically have a slightly more rounded tip as is the case with tip **1402**. However, the closer to

20   perfectly pointed the tip is, the fewer number of superlattices needed to achieve the temperature gradient between the cool temperature of the tip and the hot temperature of the hot plate.

Preferably, the radius of curvature r_0 of the curved

25   end of the tip **1402** is on the order of a few tens of nanometers. The temperature difference between successive layers of the thermoelectric material below surface **1404** approaches zero after a distance of two (2) to three (3) times the radius of curvature r_0 of the end

30   of tip **1402**. Therefore, only a few layers of the super lattice **1406-1414** are necessary. Thus, a superlattice material opposite the tips is feasible when the

electrical contact between the hot and cold plates is made using the tips of the present invention. This is in contrast to the prior art in which to use a superlattice structure without tips, a superlattice of 10000 or more

5   layers was needed to have a sufficient thickness in which to allow the temperature gradient to approach zero. Such a number of layers was impractical, but using only 5 or 6 layers as in the present invention is much more practical.

10   Although the present invention has been described primarily with reference to a thermoelectric cooling device (or Peltier device) with tipped interfaces used for cooling, it will be recognized by those skilled in the art that the present invention may be utilized for

15   generation of electricity as well. It is well recognized by those skilled in the art that thermoelectric devices can be used either in the Peltier mode (as described above) for refrigeration or in the Seebeck mode for electrical power generation. Referring now to **Figure 15,**

20   a schematic diagram of a thermoelectric power generator is depicted. For ease of understanding and explanation of thermoelectric power generation, a thermoelectric power generator according to the prior art is depicted rather than a thermoelectric power generator utilizing

25   cool point tips of the present invention. However, it should be noted that in one embodiment of a thermoelectric power generator according to the present invention, the thermoelements **1506** and **1504** are replaced cool point tips, as for example, any of the cool point

30   tip embodiments as described in greater detail above.

        In a thermoelectric power generator **1500,** rather than running current through the thermoelectric device

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from a power source **102** as indicated in **Figure 1**, a
temperature differential, T_H-T_L, is created across the
thermoelectric device **1500**. Such temperature
differential, T_H-T_L, creates a current flow, I, as
5   indicated in **Figure 15** through a resistive load element
1502. This is the opposite mode of operation from the
mode of operation described in **Figure 1**

    Therefore, other than replacing a power source **102**
with a load resistor **1502** and maintaining heat elements
10   **1512** and **1516** at differential temperatures T_H and T_L
respectively with heat sources Q_H and Q_L respectively,
thermoelectric device **1500** is identical in components to
thermoelectric device **102** in **Figure 1**. Thus,
thermoelectric cooling device **1500** utilizes p-type
15   semiconductor **1504** and n-type semiconductor **1506**
sandwiched between poor electrical conductors **1508** that
have good heat conducting properties. More information
about thermoelectric electric power generation may be
found in CRC Handbook of Thermoelectrics, edited by D. M.
20   Rowe, Ph.D., D.Sc., CRC Press, New York, (1995) pp.
479-488 and in Advanced Engineering Thermodynamics, 2nd
Edition, by Adiran Bejan, John Wiley & Sons, Inc., New
York (1997), pp. 675-682, both of which are hereby
incorporated herein for all purposes.

25   With reference now to **Figures 16A-16J**, cross
sectional diagrams illustrating a process for fabricating
thermoelements with pointed tip interfaces is depicted in
accordance with the present invention. The
thermoelements fabricated with this method may be used as
30   thermoelements for a thermoelectric cooler such as, for
example, thermoelectric cooler **200**. To begin, a pointed

tip substrate **1602** such as, for example, a silicon substrate or copper substrate peeled from silicon molds as described above, is formed as depicted in **Figure 16A.** Next, the pointed tip substrate **1602** is coated with a

5 metal layer **1604**, such as, for example, titanium (Ti) or platinum (Pt), by, for example, a sputtering or an evaporation process, as depicted in **Figure 16B.** A thin insulator **1606**, such as, for example, silicon dioxide, is deposited over the metal layer **1604** as depicted in **Figure**

10 **16C.** The valleys between tips **1610-1612** are filled with a sacrificial planarizing dielectric **1608** such that only the tips **1610-1612** of the metallic and insulator coated pointed tip substrate **1602** is exposed as depicted in **Figure 16D.**

15 Next, the sacrificial dielectric **1608** and thin insulator **1606** are etched together until the tips **1610-1612** are exposed as depicted in **Figure 16E.** A thermoelectric material overcoat **1613-1615** is then selectively grown by electrochemical methods or chemical

20 vapor deposition (CVD) over the tips **1610-1612** to a thickness of approximately five (5) nanometers as depicted in **Figure 16F.** The sacrificial dielectric **1608** is then removed as depicted in **Figure 16G.** The pointed tip substrate **1602** with pointed tips **1610-1612** is

25 mechanically aligned with a substantially flat surfaced thermoelectric substrate **1617** as depicted in **Figure 16H.** The single crystal thermoelectric substrate **1617** is polished on one side **1619** and metallized by sputter deposition of Ni **1618** on the opposite side. The end of

30 pointed tip substrate **1602** opposite pointed tips **1610-1612** is heated to approximately 550 degrees Celsius

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in order to melt the TE overcoats **1613-1615** and fuse the
TE materials on the tips **1610-1612** to thermoelectric
substrate **1617** as depicted in **Figure 16I**. Alternatively,
a current may be passed through the tips **1610-1612** to the
5   point that Joule heat melts the thermoelectric material
1613-1615 near the tips **1610-1612** in order to fuse the
tips **1610-1612** to thermoelectric substrate **1617**.

The present invention has been described primarily
with reference to conically shaped tips, however, other
10   shapes of tips may be utilized as well, such as, for
example, pyramidically shaped tips. In fact, the shape
of the tip does not need to be symmetric or uniform as
long as it provides a discrete set of substantially
pointed tips through which electrical conduction between
15   the two ends of a thermoelectric cooler may be provided.
The present invention has applications to use in any
small refrigeration application, such as, for example,
cooling main frame computers, thermal management of hot
chips and RF communication circuits, cooling magnetic
20   heads for disk drives, automobile refrigeration, and
cooling optical and laser devices.

The description of the present invention has been
presented for purposes of illustration and description,
but is not intended to be exhaustive or limited to the
25   invention in the form disclosed. Many modifications and
variations will be apparent to those of ordinary skill in
the art. The embodiment was chosen and described in
order to best explain the principles of the invention,
the practical application, and to enable others of
30   ordinary skill in the art to understand the invention for
various embodiments with various modifications as are
suited to the particular use contemplated.